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REPEATED FOUR-HOUR DIVES WITH PO_2 = 1.35 ATM

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Navy Experimental Diving Unit

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U.S. Navy divers performed multiple experimental four-hour resting dives while breathing 100% O_2 underwater at a partial pressure of 1.35 atm. Eighteen divers completed two dives with a surface interval of 44 hours, 17 completed two dives with a surface interval of 20 hours, and 16 completed five dives with surface intervals of 20 hours. Pulmonary function and symptoms were monitored before, between, and after the dives, and visual acuity was monitored during and after the series of five dives. In all cases, divers experienced a scattering of mild pulmonary symptoms or changes in pulmonary function, but no cumulative injurious effects could be seen. Recovery of pulmonary function and resolution of symptoms occurred during dives. The most severe symptoms were reported after the first of two dives, while the most severe pulmonary function change, which was asymptomatic, was seen 20 hours after the fourth dive. Only one minor change in refraction occurred, one of −0.25 diopters measurable three days after the fifth dive and persisting for about one week. Although even single four-hour dives at PO_2 = 1.35 atm entail some risk of pulmonary injury, repeated dives with surface intervals of 20 hours for up to five days do not appear to be more damaging.

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INTRODUCTION

As use of the MK 16 MOD 1 underwater breathing apparatus (UBA) increases, U.S. Navy divers are likely to be exposed more frequently to inspired partial pressures of oxygen (P_iO_2) of 1.3 atm. For some operations, divers will need to dive on multiple days, either with this rig or with oxygen rebreather UBAs. This report details some effects of repeated, four-hour underwater exposures to P_iO_2 = 1.35 atm, as specified in the task, "Pulmonary Oxygen Toxicity after Repeated Diving with Elevated Oxygen Partial Pressures."[1]

We undertook this study of repeated four-hour dives to look at pulmonary effects of two dives synchronized to time of day but conducted either daily (with a 20-hour surface interval) or every other day (with a 44-hour surface interval). We proceeded to study the effects of five daily exposures (with 20-hour surface intervals). We measured pulmonary function and assessed symptoms immediately after diving and for several days after those exposures. The pulmonary function variables were forced vital capacity (FVC), forced expired volume in one second (FEV_1), peak expired flow or maximum forced expired flow (FEF_{max}), and diffusing capacity of the lung for carbon monoxide (D_LCO). The lower limits of normal for pulmonary function variables were defined as decreases from baseline of 2.4 times the coefficient of variation (cv) found for the NEDU population — namely, 7.7% for FVC, 8.4% for FEV_1, 16.8% for FEF_{max}, and 14.2% for D_LCO.[2] We defined decreases of these magnitudes, the lower 95% confidence bands for each variable, as the lower limits of normal.

We measured visual refraction daily during the five daily dives, because we had seen hyperoxic myopia after a series of five six-hour dives.[3] Hyperoxic myopia, usually a temporary degradation of distance vision, is caused by changes in the refractive index of the lens of the eye after prolonged exposure to elevated oxygen partial pressures.

METHODS

GENERAL

Eighteen divers dove twice every other day, seventeen dove twice daily, and sixteen dove daily for five days. The dives, which were conducted in fresh water in the Navy Experimental Diving Unit (NEDU) 15-foot deep test pool, were controlled and supervised by qualified NEDU personnel. While breathing surface-supplied, humidified oxygen open circuit from MK 20 UBA full face masks, subjects rested underwater, seated or reclining on lawn furniture. The demand regulator was under between 11 and 12 feet of fresh water, providing oxygen partial pressures between 1.32 and 1.35 atm. The pressure at the very bottom of the test pool calculates to 1.44 atm.

EXPERIMENTAL DESIGN AND ANALYSIS

Before the study, subjects had not been diving while breathing air or mixed gas for at least one week or while breathing oxygen for at least two weeks. Except for their experimental dives, they refrained from diving throughout the study. Each subject's smoking behavior and history of respiratory allergies were noted. General health and use of medications also were recorded during the studies.

The subjects performed pulmonary function tests several days before the test dives, immediately before diving, within 60 minutes of leaving the water, between the dives that were conducted every other day, and on working days until the third or fourth day after the test dives. If pulmonary function variables on the last of these days were below the 95% confidence bands of baseline, they were measured again approximately one week after the dive. Each pulmonary function measurement session involved three successful repeats of each test, according to the American Thoracic Society standards.[4]

Those divers who dove daily for five days were referred to the optometry clinic at Tyndall Air Force Base for complete eye examinations during the week before diving and during the week following the last dive. Unfortunately, a second optometrist often saw the subject at the post-study visit. With those divers we also used an automatic refractometer to measure visual refraction at baseline, before and after each dive, at the session measuring post-diving pulmonary function, and one week after the fifth dive.

Divers were questioned about specific symptoms (Table 1) while they were underwater and at each pulmonary function measurement session.

Table 1. Symptoms list

During the dives:	After the dives:
Vision changes	Inspiratory burning
Ringing or roaring in ears	Cough
Nausea	Chest pain or tightness
Tingling or twitching	Shortness of breath
Light-headedness or dizziness	Lowered exercise tolerance
Chest tightness	Unreasonable fatigue
Shortness of breath	
Rapid shallow breathing	
Burning on inspiration	
Cough	

EQUIPMENT AND INSTRUMENTATION

The Collins CPX and Collins GS Modular Pulmonary Function Testing System instruments (W. R. Collins, Inc.; Braintree, MA) were used to measure pulmonary function. To measure D_LCO the equipment uses a test gas containing 0.3% carbon monoxide and 0.3% methane. A CO-oximeter (Instrumentation Laboratory; Lexington, MA) determined carboxyhemoglobin and hemoglobin concentrations from a venous blood sample. An automatic refractometer (Model 530, Allergan Humphrey; San Leandro, CA) was used to measure visual refraction.

Divers breathed surface-supplied oxygen from MK 20 open circuit UBAs. The oxygen was humidified by being passed through bubblers built for the purpose. We confirmed that the passing gas stream had absorbed water by measuring the water volume before and after some of the dives. Communication units were included in the UBA facemasks.

PROCEDURES

Before each dive, the diver subjects reported to the laboratory, where flow volume loops were measured. A diver for whom any flow volume loop variable had decreased by twice the 95% confidence band was prohibited from diving. For subjects who dove for five days, visual refraction was recorded. Any diver for whom refraction had changed by –0.5 diopters (D) or more from baseline was prohibited from diving.

Under the dive supervisor's direction, the diver subjects then entered the water at about 10-minute intervals. During the dives, subjects relaxed in lounge chairs on the bottom of the test pool, where they watched movies. They were permitted to surface, breathe room air, and eat or drink for no more than five minutes per hour. Water temperature was 90 ± 5 ºF (32 ± 3 ºC). Divers were dressed for comfort, most in swim trunks and T-shirts, but a few in wetsuits. They were questioned about specific symptoms (Table 1) once per hour while they were underwater.

At the end of the four hours, divers were instructed to surface and leave the water. During their first ten minutes on the surface, they were escorted and monitored for ill effects from surfacing. During or after the ten-minute period, a blood sample was drawn to measure hemoglobin and carboxyhemoglobin, visual refraction was tested, and pulmonary function was measured. Additionally, the divers completed the postdive questionnaire and instilled a solution of 2% acetic acid and aqueous aluminum acetate into their ear canals to prevent infections.

To record flow volume loops, a subject wearing nose clips breathed on a mouthpiece into and out of a spirometer. The subject first breathed normally, then inhaled rapidly and as fully as possible before exhaling with maximum force,

and then fully inhaled. Measurements of FVC, FEV_1, FEF_{max}, and other variables were read from the flow volume loops.

The single-breath technique was used to measure D_LCO: the subject exhaled as far as possible, inhaled as much of the test gas from the spirometer as possible, and then held his breath for 10 seconds. The variables used to obtain D_LCO were calculated from the gas concentrations before and after the breath-hold. Adjustments were made for carboxyhemoglobin and hemoglobin concentrations.[5] Volumes expired before the gas concentrations were measured and the volumes of gas over which the concentrations were averaged were adjusted to ensure that the analyzer signal was stable when measurements were recorded.[6]

While subjects looked into the automatic refractometer, refraction was measured one eye at a time. We made a subjective measure of acuity from the machine by determining the smallest line of text the divers could read. The machine gave readings of two radii of lens curvature needed to focus an image reflected off the retina, the angularly symmetrical lens ("sphere"), and the astigmatism, an additional radius of curvature ("cylinder") at some angle ("axis"). Both spherical and cylindrical refractions were read in increments of 0.25 D, and axes were read in increments of one degree. We took triplicate measurements at baseline and after the dives and averaged them, but we used only single predive measurements to assess whether a subject could dive. Had a reading been 0.5 D or more below the baseline average, two other readings would have been taken and their average used to confirm whether the abort condition was met.

RESULTS

PULMONARY EFFECTS

Pulmonary results from the four-hour dives are shown in Tables 2-4. Subject numbers are arbitrary and independent among the tables; each study began with "subject 1", and divers were assigned new numbers each time. Pulmonary function variables found to be low after a dive or before the next dive are listed under the dive most closely preceding the finding. If a value was low both immediately after a dive and the following morning before the next dive, the lower of the two values is listed. Symptoms also are listed under the dive that most closely preceded their report: for example, symptoms reported immediately after Dive 1 and those on the morning before Dive 2 are ascribed to Dive 1.

All pulmonary function values were within the normal range around baseline by ten days after diving; we were unable to measure daily to follow the time course of recovery. For most subjects, variables were within the normal range around baseline by three to four days after diving, when all symptoms had resolved.

Symptoms and changes in pulmonary function occurred separately or together.

Table 2. Decreases from baseline in pulmonary function, pulmonary symptoms
Two dives, 20-hour surface interval

Pulmonary signs and symptoms; two repetitions, 20-hour surface interval **n = 17**	**Dive 1**	**Dive 2**		**Later**
Subject 1	FEV_1 9.5%	i, c		c
Subject 2	c	FEV_1 11.2% FVC 8.4% c		c
Subject 3	c	FVC 16.2%		t, d
Subject 4	c, t	FEV_1 9.7%		FEV_1 10%
Subject 5		FEF_{max} 22%		FEF_{max} 22%
Subject 6				FEV_1 9.9%
Subject 7		D_LCO 15.8%		D_LCO 17.9%
Subject 8		D_LCO 14.6%		
Subject 9	t	t, c		
Subject 10	t			
Subject 11	t			
Subject 12	i, t	C		
Subject 13	i	I		
Subject 14	i			
Subject 15		C		
Subjects 16, 17			No signs or symptoms	

Symptoms: t = chest tightness, i= inspiratory burning, d = dyspnea, c = cough

All symptoms were mild. PFT values were depressed below 2.4 coefficients of variation (cv) of baseline, but to less than 4.8 cv below baseline. "Dive 2" includes data from the first day after the second dive, while "Later" contains events more than one day after all diving.

Table 3. Decreases from baseline in pulmonary function, pulmonary symptoms
Two dives, 44-hour surface interval

n = 18	Dive 1	Dive 2		Later
Subject 1	FEF_{max} -26% **c, t, i**	FEV_1 8.5% c, d		
Subject 2	t	D_LCO -17.0% t		
Subject 3	i	FEV_1, 11.9% i, t		
Subject 4	i	i		FEV_1 9.9% FVC 8.0%
Subject 5	i, c	i		FEV_1 -8.4%
Subject 6				D_LCO -15.2%
Subjects 8-18			No signs or symptoms	

Symptoms in bold were moderate. All PFT changes were more than 2.4 cv below the baseline, but less than 4.8 cv below it. "Dive 2" includes data from the first day after the second dive, while "Later" contains events more than one day after all diving.

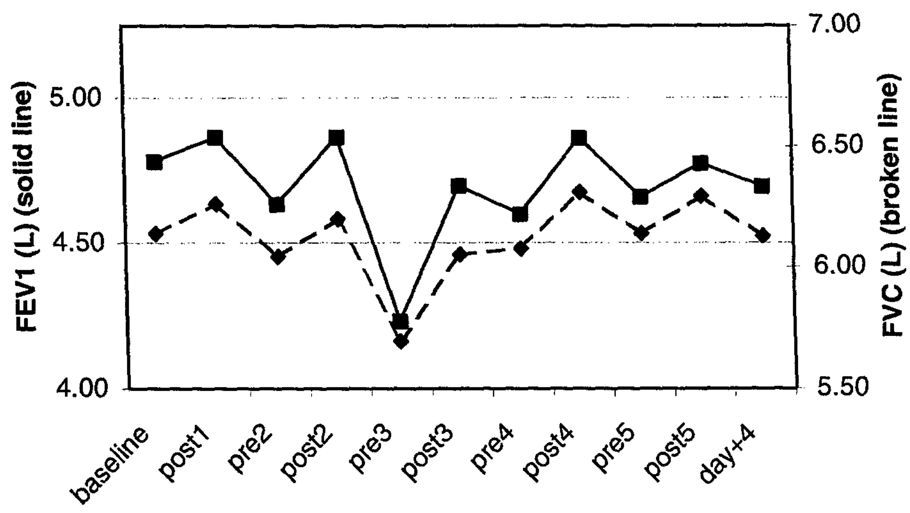
Table 4. Decreases from baseline in pulmonary function, pulmonary symptoms
Five repetitions, 20-hour surface interval

n = 16	**Dive 1**	**Dive 2**	**Dive 3**	**Dive 4**	**Dive 5**	**Later**
Subject 1	FEV$_1$ 9.0%	FEV$_1$ 11.2% FVC 7.9%			**i**, t	
Subject 2		FEV$_1$ 11.5% FEF$_{max}$ 20% c	c	c, t	c, t, i (D$_L$CO) 13%	
Subject 3				**FEV$_1$** 17.5%** **FVC** 13.9%	D$_L$CO 14%*	FEV$_1$ 8.9% FVC 10.6%
Subject 4	I	i	i			
Subject 5	C	c, t	i		t	
Subject 6			c, i			
Subject 7			c	C		
Subject 8			i	I		
Subjects 9-16	No signs or symptoms					

* Baseline was low. Subject was assessed relative to post–Dive 1 values.
** Subject did not perform Dive 5. Similar timing of testing was maintained.

Symptoms in bold were moderate. PFT variables in bold were depressed by more than 4.8 cv from the baseline. Those in normal type were depressed more than 2.4 cv but less than 4.8 cv from the baseline. Those in parentheses were less than 2.4 cv below the baseline but more than 2 cv from it. “Later” includes changes three or more days after the last dive, that is, after the weekend.

The changes in pulmonary function variables were often sudden, and recoveries occurred although diving continued. The time course for subjects 2 and 3, who showed decreased pulmonary function after the fifth dive, and for subject 16, a diver with neither symptoms nor signs of pulmonary oxygen toxicity, are plotted in Figures 1–3.



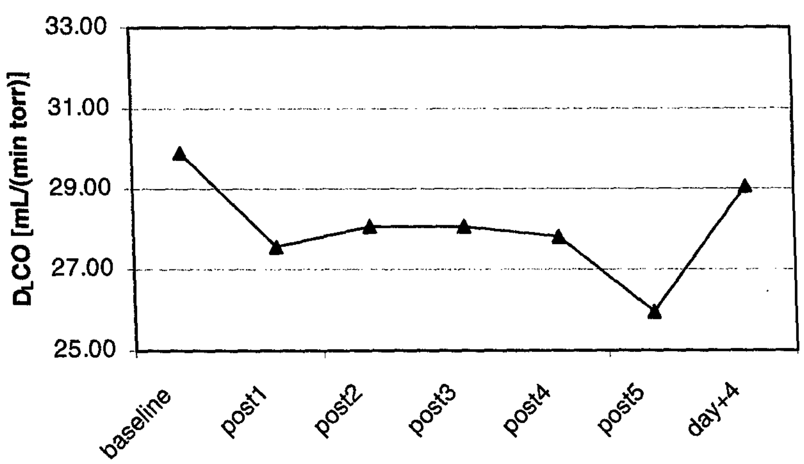


Figure 1. Pulmonary results from Subject 2, five days of diving. This subject had decreased FVC and FEV_1 before the third dive, but these values recovered during the dive and remained near the baseline for the duration of the measurements. The D_LCO values did not change with Dives 2 or 3, but they diminished after the fifth dive.

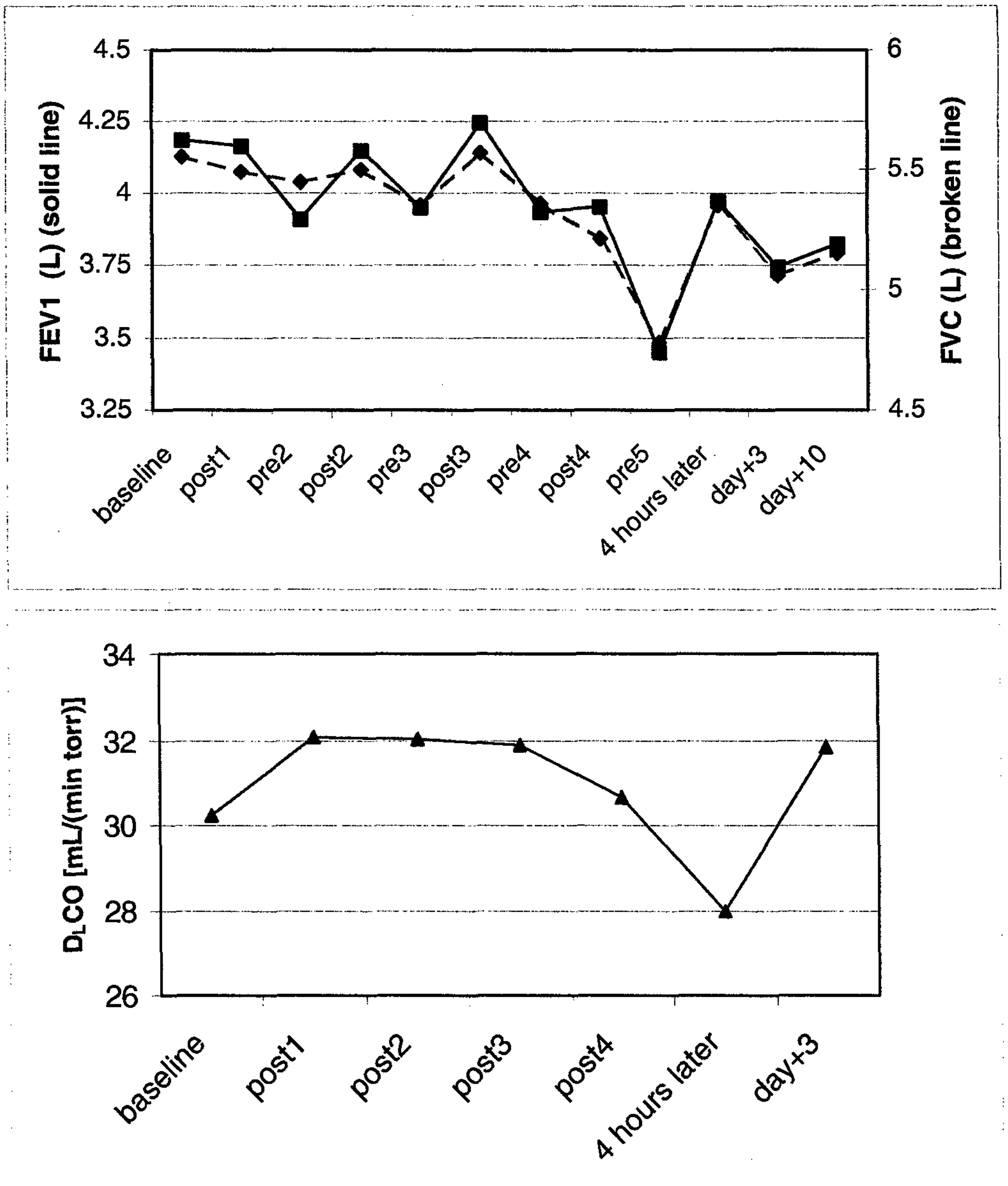


Figure 2. Pulmonary results from Subject 3, five days of diving. Note the sudden drop and rapid recovery in FVC and FEV_1. This subject did not perform the fifth dive, because his FEV_1 was outside the allowable value. His D_LCO was depressed after his FVC and FEV_1 had recovered.

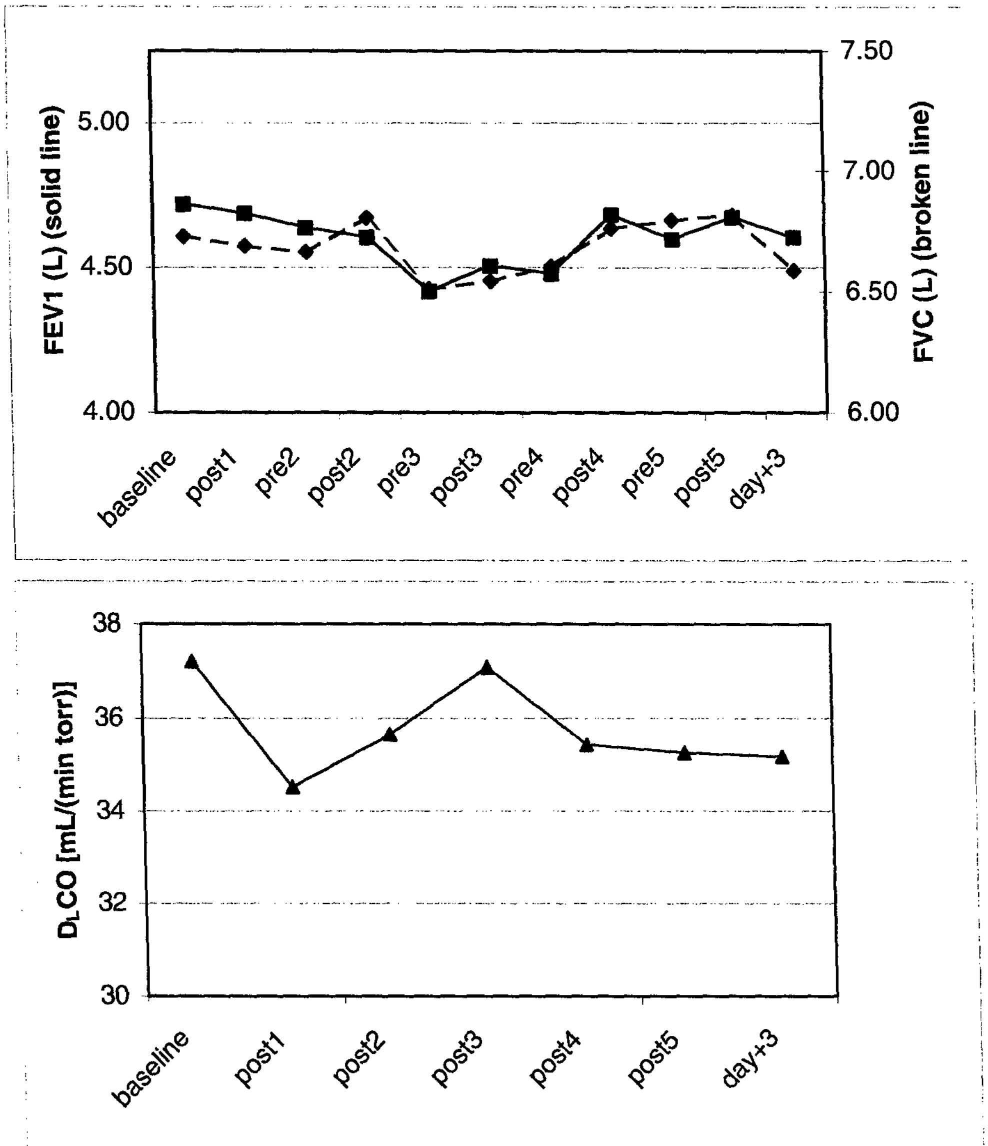


Figure 3. Pulmonary results from Subject 16, five days of diving. This subject showed no significant changes or trends in FVC, FEV_1, or D_LCO.

Table 5.
Single dives, previously reported[2], for comparison with Tables 2-4.

Breathing gas was 100% oxygen

n = 8	Dive 1		Later
Subject 1	FEF_{max} 21%		
Subject 2	D_LCO 12%		
Subject 3	i, c, t, d		
Subjects 4-8		No signs or symptoms	

Breathing gas was air

n = 8	Dive 1		Later
Subject 1	c		
Subject 2	i		
Subject 3	c		d
Subject 4			D_LCO 14.5%
Subjects 5-8		No signs or symptoms	

EFFECTS ON VISION

One diver had a very mild myopic shift (–0.25 D) after five days of diving. Because this change in refraction is at the limit of the measurement resolution, to decide that it occurred we rely on a combination of the refraction measurements and the diver's observation that he could see near objects more clearly. These subtle, partially subjective changes in vision became evident at least a day after the last dive, and the refraction change was measured four days after the last dive. The refraction difference was no longer measurable by the seventh day after that last dive, and the subjective changes disappeared also at about that time.

One diver had a reduction in subjective visual acuity as determined with the refractometer from 20/30 (right), 20/25 (left) to 20/60 (right), 20/50 (left) after the fourth dive, with no measurable change in refraction but the complaint of blurriness. In brighter light, acuity measured with the wall chart was 20/40 for both eyes. After the fifth dive, acuity measured with the refractometer was 20/40 in both eyes, and four days after the fifth dive, it was 20/20 in both eyes.

OTHER EFFECTS

Ear pain and fatigue were reported only in conjunction with the five-day dives. Ten of 16 subjects reported ear pain (Draeger ear) caused by gas absorption

from the middle ear. Only two divers reported unusual fatigue: one, the day after Dive 2; the other, the first days after Dives 2, 4, and 5. One diver reported mild nausea shortly after Dive 4.

Four of 16 subjects reported itching of unclothed arms and legs during the five-day series, with onset after Dive 3 or Dive 4. Two of the divers described it as a sensation like that caused by fiberglass splinters. However, at no time during these dives was the free chlorine concentration higher than 2.0 parts per million, nor was the bound chlorine measurable — and pH levels ranged from 7.2 to 7.4. The warmth of the water may have contributed.

DISCUSSION

We were surprised to see no accumulation of pulmonary injury with even five days of diving. The 20 hours between dives may be sufficient for recovery. In fact, divers commented that the diving seemed more comfortable after the third dive of the five, and that a second dive (with a 20-hour surface interval) removed the symptoms caused by the previous dive. None of the measurements is sensitive enough to detect an acclimatizing effect, but such an effect is plausible. By increasing the production of protective materials after repeated exposures, the body can protect itself from many mild injuries.

The incidence of pulmonary function change in each group can be described as the ratio of the number of subjects with to the number of subjects without a measurable change. Fisher's exact test is used to compare those proportions between two conditions. Neither the proportions for pulmonary function changes nor those for pulmonary symptoms differed statistically among our diving conditions. Even single four-hour dives with $P_iO_2 = 1.35$ atm sometimes resulted in pulmonary function changes or symptoms (Tables 2–5), as did single four-hour dives with air as the breathing gas (Table 5).

Although the sample size is too small to allow us to say that the pulmonary results of these exposures are not different, we have enough data to state that no major differences in pulmonary function result after one, two, or five days of diving with $P_iO_2 = 1.35$ atm, no major improvement results from increasing the surface interval to 44 hours, and no clear cumulative injury is apparent with a 20-hour surface interval. The only symptoms worse than mild ones occurred after the first dive, and then on the day between dives during the two dive series with 44-hour surface intervals. The only severe decreases in pulmonary function occurred after four days of diving (Fig. 2), but the changes were abrupt. Furthermore, resolution of some symptoms and recovery of pulmonary function occurred during the five-day period of diving, as we can see in Table 4 and Figure 1.

All reported pulmonary function values are the mean of three consistent efforts. In many cases, the first or the first two flow volume loop maneuvers resulted in lower values than did subsequent attempts, and values from the first were discarded as results of poor efforts. However, the first reading may have been real in a majority of cases; it may have represented either a lung engorged after diving and breathing oxygen or a lung with some alveoli collapsed by oxygen absorption from poorly ventilated regions. Several divers commented on the need for a first effort "to clear out the lungs." In either case, an increased volume of blood in the lung after immersion and loss of regional hypoxic vasoconstriction is physiological, not pathological, as is absorption atelectasis without surfactant damage.

Repeated four-hour dives did not cause significant change in visual refraction. One diver showed a definite, small refractive change, and one a short-term change in visual acuity without a change in refraction. Until we know more about thresholds for hypoxic change, monitoring refraction before and after repeated high P_iO_2 dives appears to be important.

Draeger ear becomes a significant nuisance with repeated breathing of high oxygen partial pressures. Preventative measures could be useful to Navy divers.

CONCLUSIONS

Although single four-hour dives at $P_iO_2 = 1.35$ atm can provoke mild to moderate respiratory symptoms and changes in pulmonary function variables, repeated dives with a 20-hour surface interval do not appear to increase the incidence of respiratory problems in comparison to that of single dives. A 44-hour surface interval is not notably better than a 20-hour interval. Middle ear and skin problems must be considered, and, until hyperoxic myopia in the water is better understood, vision should be monitored if dives are to be repeated more than twice in three days.

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